CONTACT EFFECTS ON SILICON SURFACE FLASHOVER STUDIES

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ABSTRACT

We studied the breakdown of n^+nn^+ silicon devices in vacuum and various dielectric fluids. The breakdown voltage exhibited a dependence on the abruptness of the high-low junction and on the dielectric constant of the surrounding dielectric liquid.

INTRODUCTION

Silicon surface breakdown requires that the length of a photoconductive switch be greater than a certain value. Since the "on" resistance is proportional to the square of the length for a given optical trigger energy [1], a shorter switch will be more efficient.

Experiments with a set of plane parallel electrodes were conducted to study surface flashover of n^+nn^+ silicon devices. These devices exhibited breakdown at fields at least an order of magnitude lower than the bulk silicon breakdown field. The breakdown voltage (BV) also showed a dependence on the abruptness of the high-low junction.

The BV of these devices was measured in air, transformer oil, glycol and de-ionized water. The BV increased with the dielectric constant of the surrounding media.

EXPERIMENT

Ohmic n^+nn^+ devices were fabricated beginning with 2500-3000 Ω-cm n type (111) silicon. The diffusion was performed with a solid phosphorous source wafer. There were two sizes of rectangular solid devices. The short devices were 0.2 cm square and 0.08 cm between the n^+ layers, while the long devices were 0.2 cm x 0.8 cm and 0.81 cm between the n^+ layers. The short devices had a one hour drive-in or an eighteen hour drive-in in a nitrogen atmosphere. The long devices had a four hour drive-in in a nitrogen atmosphere.

Cylindrically symmetric stainless steel electrodes were used to obtain a uniform field. The experimental setup is shown in Fig.1. A wide-band current sensing coil with a sensitivity of 0.5 volts per amp was used. A 1000:1 voltage probe measured the voltage across the device. The high voltage source was a Velonex Model 350 high power pulser with a rise time of approximately four microseconds. Breakdown was said to occur when a sharp rise in current accompanied a sharp fall in voltage. Measurements were made in a 10^{-6} Torr vacuum, air, transformer oil, glycol and de-ionized water.

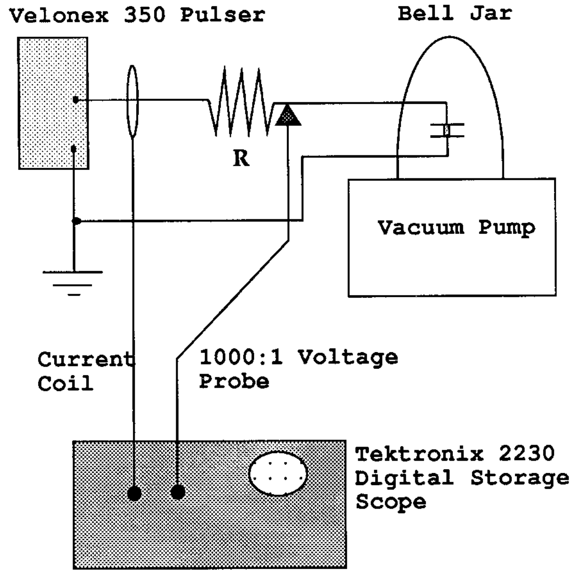

Fig. 1. Experimental arrangment for studying surface breakdown.

OHMIC CONTACT DEVICES

The n^+nn^+ devices exhibited ohmic behavior for current densities less than en_0v_s, where e is the charge on an electron, n_0 is the background electron concentration and v_s is the electron saturation velocity.

High-low junctions have a large built-in field [2] in the absence of an external potential. Fig.2 is a plot of the equilibrium field at an abrupt n^+n junction with doping of $10^{19}cm^{-3}$ on the high side and $1.7x10^{12}cm^{-3}$ on the low side. The peak field is 171 kV/cm. This fact by itself is not sufficient to cause breakdown as the ionization integral is much less than one. However, the field at the anode is further enhanced under an applied voltage. When the current density J exceeds the value that n_0 can support, excess carriers are injected from the cathode to support the current. This results in a net space charge which increases the field at the anode above the average field value.

We solve for the anode field vs the current density neglecting diffusion current and take $n(x) = n_0 + n'(x)$, where $n'(x)$ is the excess injected electron density. We use the following empirical expression [3] for the mobility $\mu(x)$,

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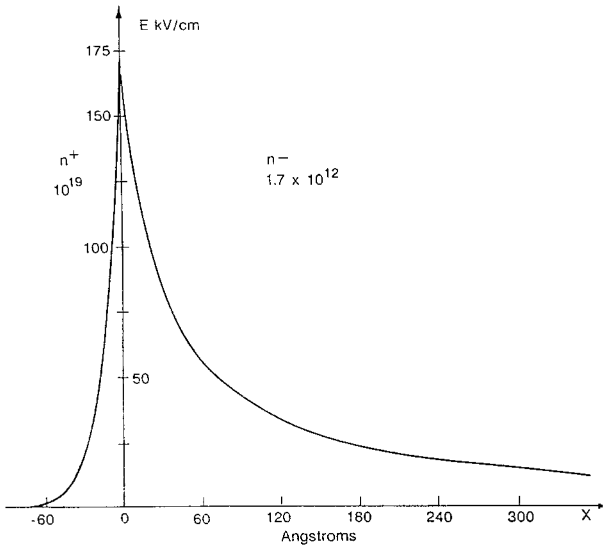

Fig.2. Plot of equilibrium electric field at high-low junction

$$\mu(x) = \frac{\mu_0}{1 + 6E(x)/E_s} \qquad (1)$$

which underestimates the actual mobility with a maximum error of 20%. Using Poisson's law and the relation between current density J and the carrier density we find that

$$\frac{-JL(6-J_s/J)^2}{\varepsilon\mu_0 E_s^2} = \frac{E_A}{E_s}(6-J_s/J)+\ln\left(1+\frac{E_A}{E_s}(6-J_s/J)\right), \qquad (2)$$

where $J_s = qn_0\mu_0E_s$, ε is the dielectric constant of silicon, E_A is the field at the anode and L is the device length. Eqn.(2) is a transcendental relation between E_A and J which can be solved numerically. We can also get an analytical relation for the current density versus voltage V,

$$J = \frac{\varepsilon\mu_0 E_s E_A^2/2 + J_s V}{E_s L + 6V} \qquad (3)$$

This shows that the anode field is larger than the average field (V/L). Fig.3 shows a plot of E_A, V/L and JA versus V based on Eqn.'s (2) and (3), where A is the cross sectional area of the short devices, 0.04 cm^2.

To investigate the effect of the built-in field, the abruptness of the high-low junction was varied. Devices with a one hour drive-in time and an eighteen hour drive-in time were fabricated. The longer the drive-in time, the less abrupt the junction becomes. This should result in a lower built in field at the junction. Thus the devices with the eighteen hour drive-in should have a larger breakdown voltage. Table I shows that this was indeed the case. The two values given correspond to two different polarities. One is lower than the other since the devices were asymmetrically placed with respect to the phosphorous source wafer during the diffusion pre-deposition. Therefore one side is more highly doped than the other. The lightly doped side has the higher breakdown value.

Fig.3 shows the I-V data for one each of the one hour and eighteen hour devices. Both polarities were applied to these devices to ensure they were symmetric.

Table I. Results of breakdown tests on ohmic and p-n devices.

Length (cm)	Drive-in Time (hours)	Breakdown Voltage (volts)	Device
0.08	1	1030/675	$n^+n\,n^+$
0.08	18	1200/815	$n^+n\,n^+$
0.08	4	1100	$p^+n\,n^+$
0.81	4	16,000	$n^+n\,n^+$
0.78	4	8200	$p^+n\,p^+$

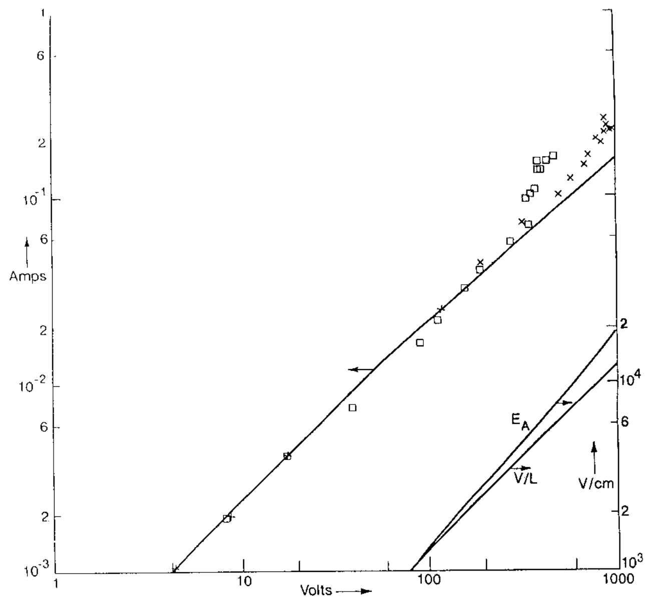

Fig.3. I-V for n^+nn^+ device. Box is for one hour and "x" is for eighteen hour drive-in device. Solid lines are theoretical curves for I, E_A and V/L vs V. Device area = 0.04 cm^2.

For comparison purposes a p^+nn^+ device was also made and tested under reverse bias. This device had the same dimensions as the short n^+nn^+ device.

There was no visible light emission from any of these devices. It should be noted that breakdown occurred after J exceeded qn_0v_s for the n^+nn^+ devices. The standard deviation, per device, of the BV and breakdown current was about 10%.

The long n^+nn^+ devices were also tested with the results given in Table I. These devices exhibited visible flashes of light during their breakdowns. Glow discharge cleaning with Argon did not result in any change in the breakdown values. There was significantly more scatter in their breakdown values.

As a result of the enhanced anode field, avalanching due to collision-ionization occurs. This injects minority carriers (holes) into the n region thus increasing the conductivity. This leads to a further increase of the field at the anode thus providing positive feedback for the breakdown.

Field enhancement due to space charge injection in high-low junctions is a well known phenomenon [4], [5]. Based on the differing breakdown values for the one hour and eighteen hour drive-in devices we conclude that the built-in field at the high-low junction plays a role in satisfying the breakdown condition.

SURFACE CHARGE AND FLASHOVER

In 1956 Garrett and Brattain [6] proposed a theory of p-n junction surface breakdown based on an enhanced field at the junction at the surface. They showed that given a positive charge at the surface of a p^+n junction the depletion region on the n side of the junction was likely to shrink since the positive surface charge could terminate some of the field lines of the negative charge in the p side depletion region. Since the potential difference across the depletion region must be the same, the field at the surface must be higher than that in the bulk.

Garrett and Brattain also noted that a high dielectric constant coating (castor oil) increased the breakdown voltage.

We examined the field dependence at the silicon-dielectric interface theoretically with the following simple model. Assuming some arbitrary distribution of surface charge σ_s at the boundary between dielectric ε_2 and ε_1 with conducting plates at y=0 and y=a, as shown in Fig. 4, one may solve Laplaces equation for the electric field in the y direction, E_y at x=0 to yield

$$E_y(0,y) = \frac{-2}{(\varepsilon_1+\varepsilon_2)} \sum_{n=1,2,3...} B_n \cos(k_n y) \qquad (4)$$

where $k_n = n\pi/a$, and B_n is given by

$$B_n = \int_0^a \sigma_s \sin(k_n y)\, dy \qquad (5)$$

Therefore, the electric field along the interface due to the surface charges is inversely proportional to $(\varepsilon_1+\varepsilon_2)$.

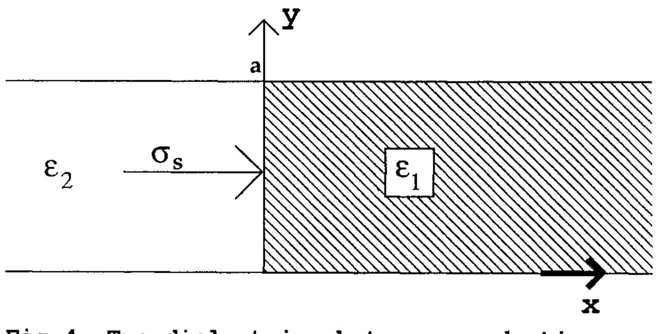

Fig.4. Two dielectrics between conducting plates with surface charge at the interface.

We have measured the BV for a number of devices in air (ε_r=1), transformer oil (ε_r=2.2), glycol (ε_r=40) and deionized water (ε_r=80). The BV increased as the dielectric constant of the liquid increased as shown in Table II. G.M. Loubriel et al at Sandia [7] have also found that de-ionized water surrounding their silicon samples significantly increased the breakdown voltages. These results point toward surface charge playing a major role in the breakdown process.

Table II. Breakdown Voltages of n^+nn^+ devices in dielectric fluids.

Dielectric Constant	Breakdown Voltage
1.0	1100/800
2.2	1100/800
40	1800/1600
80	2300/1000

In making contact to silicon either with an n^+n, p-n or metal-semiconductor contact there is a space charge region present. If there is surface charge in the vicinity of this high field region, the field along the surface may be enhanced above the bulk value as explained by the theory presented by Garrett and Brattain.

CONCLUSION

The built-in field at a high-low junction plays a role in silicon surface breakdown. The more abrupt the junction, the lower the BV.

There are high field regions present at semiconductor contacts, including "ohmic" contacts. An enhanced field at the surface due to surface charge in the vicinity of the contact could explain the surface breakdown at low average fields. The enhanced field leads to breakdown by collision-ionization at the surface. The effects of the surface charge can be mitigated by high dielectric constant coatings. The flashover phenomenon may well be breakdown in a subsurface layer accompanied by light emission. As has been reported [8] there is a broad spectrum of visible light emission in silicon during breakdown.

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